P/DDMO

FOR OFFICIAL USE ONLY

M.R.P. 926
S.C.I/101
22nd August, 1955.

AIR MINISTRY

METEOROLOGICAL RESEARCH COMMITTEE

A comparison of heights obtained from a radar altimeter and a pressure altimeter

by
W. G. Durbin (Meteorological Office)

Summary

Simultaneous readings of the altitude of a Canberra aircraft as indicated by a Mk. VI radar altimeter and the standard Mk. [illegible]XA pressure altimeters in the pilot's and navigator's positions were made on seven flights up to a height of about 50,000 ft. Readings of outside air temperature, frost point and airspeed were made simultaneously. Comparisons are given between:-

(a) Radar altimeter readings and corrected pressure altimeter readings.

(b) Radar altimeter readings and heights computed from the corrected pressure indicated by the pressure altimeter and the measured air temperature and humidity.

In almost every case the radar altimeter gave the higher reading. The differences increased with height and at 50,000 ft. the difference computed by method (a) was always over 1100 ft. and sometimes over 2000 ft. Differences obtained by method (b) were considerably smaller, 130 to 1020 ft. There was a consistent difference between the two pressure altimeters carried, which also increased with height and averaged 550 ft. at 50,000 ft.

It is concluded that a pilot flying at an indicated height of 50,000 ft. using a pressure altimeter may be as much as 2,000 ft. in error. This is not entirely due to the difference between the standard ICAN atmosphere and the actual atmosphere but to an appreciable extent to errors in the pressure altimeter system. These may either be instrumental or arise from incorrect position (pressure) errors. There is no reason to suspect errors of greater than about 150 ft. in the radar altimeter readings.

1. Introduction

Early in 1954 a Mk. VI radar altimeter was installed in Canberra WJ582, an aircraft held by the Meteorological Research Flight. It is of great importance in atmospheric analysis to know as accurately as possible the heights at which measurements are made and it was hoped that the radar altimeter would prove a valuable aid in this respect. In particular it was hoped that it would enable accurate determinations of height at which temperature, humidity and ozone readings are taken and also serve as a check on pressure altimeter heights used in the determination of speed correction coefficients of aircraft thermometers.

This instrument was a prototype lent by Radio Dept., R.A.E. primarily for the purpose of checking its characteristics and operational performance. In fact, up to the present it has functioned continuously and has required very little attention. Good signals have been received at all heights up to 50,000 ft.

/over

FOR OFFICIAL USE ONLY

over both land and sea using only the small dipole aerials installed under the fuselage.

The purpose of this note is to present a comparison between the height readings obtained from the radar altimeter and two pressure altimeters in the same aircraft.

2. Flight procedure

Ascents to about 50,000 ft. are frequently made in the Canberra aircraft held by the Meteorological Research Flight. During these flights and at about fifteen different heights, simultaneous readings of temperature, frost point, height read from a pressure altimeter and airspeed are taken. On seven flights made over the sea during July and August, 1954, readings were also taken of the radar altimeter and these were subsequently compared with the heights obtained from two pressure altimeters, one in each of the pilot's and navigator's positions, after these latter had been corrected for instrument, setting and position (pressure) errors and departures from the ICAN standard atmosphere.

3. Method of obtaining true heights from pressure altimeter readings

(1) By integrating the weight of a column of dry air, it is shown (1) that the thickness z ft. of a layer with mean temperature T° K and pressures p_o mb. at its base and p mb. at its top is given by

$$z = 221.1\ T\ (\log p_o - \log p) \qquad (1)$$

The thickness of a layer of moist air is slightly greater than that for dry air by an amount that can be allowed for by replacing T in equation (1) by the mean virtual temperature of the layer, T_m.

(2) The indicated temperatures at the levels at which readings were taken were corrected for airspeed using the equation

$$T_c = T_i - \alpha\left(\frac{V}{100}\right)^2 \qquad (2)$$

where V is the true airspeed in kt., T_c and T_i are the corrected and indicated temperatures in degrees Fahrenheit and where α, the speed correction coefficient for this aircraft, was previously determined to be 1.76 (2).

(3) Virtual temperatures were computed from T_c using the equation

$$T_m = \frac{T_c}{\left(1 - \frac{3e}{8p}\right)} \qquad (3)$$

where p is the pressure at which a reading was taken, e is the vapour pressure and T_m, the virtual temperature, and T_c are in degrees Kelvin.

(4) p_o and p were obtained directly from the pressure altimeter readings which, after being corrected for instrument, position (pressure) and setting errors, were converted directly into pressures on the ICAN scale.

(5) Virtual temperature ascents were plotted on Te-Phi-Grams for the individual flights and the values of the mean virtual temperatures for each of the layers bounded by the pressures at which readings were taken were obtained by the method of equal areas.

/(6)

(6) The thicknesses were calculated from equation (1) above (using T_m as the mean temperature) in steps varying between 2,000 ft. and 5,000 ft. and added together to give the true heights at which the readings were taken up to the ceiling of about 50,000 ft.

4. Results

The results are given in Table 1 and Fig. 1. Table 1 shows the differences between the radar altimeter heights and the indicated and integrated heights obtained from both the pilot's and navigator's pressure altimeters for the individual flights.

Fig. 1 shows the corresponding mean curves for these flights for heights between 5,000 ft. and 50,000 ft., 5,000 ft. being the lowest height for which data were available for all seven flights.

From Fig. 1 it is seen that:-

(1) the radar altimeter gives readings which are greater than the heights calculated from the pressure altimeter readings by amounts that increase with height from about 100 ft. at 5,000 ft. to about 800 ft. at 50,000 ft. for the navigator's altimeter and from about 90 ft. at 5,000 ft. to just under 250 ft. at 50,000 ft. for the pilot's altimeter.

(2) the difference between the navigator's pressure altimeter indicated heights (corrected for setting error only) and the radar altimeter heights increases from about 180 ft. at 5,000 ft. to just under 2,000 ft. at 50,000 ft.

These latter differences have been computed because normally an altimeter is set to QNH and no subsequent allowance for instrument or pressure errors is made. It will be seen that curves 1 and 2 closely resemble each other and that at some points pressure and instrument errors cancel each other out.

It has not been thought necessary to plot the corresponding curve for the pilot's altimeter because it would differ from curve 3 exactly as curve 1 differs from curve 2.

(3) after correcting both pressure altimeters for instrument, position (pressure) and setting errors, the indicated heights from the navigator's altimeter were greater than those from the pilot's altimeter by amounts that increased from a negligible amount at 5,000 ft. to between 500 and 550 ft. at 50,000 ft.

Comparison of Table 1 and Fig. 1 shows that the differences for the individual flights can differ appreciably from the mean values and Table 2 gives the maximum, minimum and mean differences at two heights, viz. 5,000 ft. and 50,000 ft.

5. Discussion

Prior to the introduction of a radar altimeter there was no absolute method of checking heights computed from pressure altimeter and temperature readings. The accuracy of these heights depends on the accuracy with which true air temperature can be obtained and is affected by hysteresis and other errors inherent in the pressure altimeter system. It is not really surprising, therefore, that there are differences between the heights obtained from the readings of the two types of altimeter.

Although it has not yet been established that the radar altimeter gives heights which are nearer the true heights than those calculated from the pressure altimeters, it seems most likely that this is so. Firstly, the readings of the

/two

two pressure altimeters, when corrected for their respective instrument errors, differ by amounts that increase with height and this suggests the existence of an error peculiar to the pressure altimeter itself and which present methods of calibration fail to detect. Another possible explanation for the difference between the readings of the two pressure altimeters is that the position (pressure) errors are affected by the piping connected to the altimeters. In this respect it would be of interest to carry out two high level ascents in the same air mass with the altimeters interchanged for the second ascent. The position errors calculated for the Canberra aircraft of the Meteorological Research Flight are shown graphically in reference 2, the method used being that of Aero Report No. 2299 (3). In this, position errors found near the ground are extrapolated to height using the Glauert relation. A comparison of position errors obtained by an essentially similar method due to Weaver (4) and by flight measurement of position errors using a trailing static head is given for a Meteor VII aircraft in a report by K. W. Smith (5). The following is an extract from the summary of the report.

"At small values of C_L (lift coefficient) the measured position error agrees approximately with that predicted from the aneroid test results by the Glauert law as far as M (Mach No.) $\simeq$ .75. Above this Mach number Weaver's or Charnley's use of the Glauert two-dimensional linearised subsonic flow theory substantially underestimates the measured position error.

At large C_L's the Glauert theory appears to break down at comparatively low Mach numbers. ($M \simeq 0.5$)".

(The lift coefficient for an aircraft in level flight is found from the equation

$$C_L = \frac{W}{\frac{1}{2}\rho_o V_i^2 S}$$

where W is the weight of the aircraft, ρ_o is the density of the air at ground level, V_i is the equivalent airspeed and S is the area of the wings. For W in pounds, ρ_o in slugs/ft.^{3}, V_i in kt. and S in ft.^{2}, C_L varies between 0 and 1. It will be seen from the above equation that for a given aircraft a large lift coefficient is associated with a low indicated airspeed.)

These results must be treated with reserve when considered for a Canberra aircraft, but is seems likely that in essence they will apply. It has been calculated that from 30,000 ft. to 40,000 ft. C_L rises from about 0.15 to about 0.3 at a constant Mach number of about 0.73. From 40,000 ft. to 50,000 ft. C_L rises to about 0.5 while, due to fall off in aircraft performance, the Mach number falls to about 0.6. From these figures and the above results it seems that the Glauert relation will hold, certainly up to 40,000 ft. and probably up to 45,000 ft. The position at 50,000 ft. is more doubtful, but an inspection of Fig. 1 suggests that the error from this cause even at this height is not great. An estimate by Mr. K. W. Smith of R.A.E. is that it does not exceed 50 ft.

The author has been informed by Radio Dept., R.A.E. that errors in the radar altimeter are not likely to exceed 150 ft. and are constant with height. The transmitted pulse from the radar altimeter is rectangular and displays a sharp leading edge on the cathode ray tube whereas the reflected pulse, which is received from a certain ground area, has a sloping leading edge. Over rugged country or a rough sea the reflected pulse may be weak and may be rendered more visible by increasing the gain control. This is done at the expense of receiver noise which obscures part of the leading edge. An error in assessing the point at which the reflected pulse cuts the time base is thus introduced and for a very weak signal may amount to one pulse length which corresponds to 150 ft. of

/height

height. Under the conditions of the present series of experiments, errors should have been very much smaller.

Evidence of the agreement between two radar altimeters has been obtained by flying two Canberra aircraft side by side at various levels up to 48,000 ft. (Ref. 6, unpublished). Up to 44,000 ft. the aircraft were never more than about 200 yd. apart, and the difference between the altimeter readings never exceeded 100 ft. Above this level the results are unreliable, owing to a wide separation of the two aircraft.

Ref. 6 also contains a report on the checking of a radar altimeter by the method of map scaling of photographs of the ground taken from the air. It was found that the radar altimeter readings were greater than the scaling heights by amounts, the maximum of which, at heights up to about 40,000 ft., was 220 ft. at a radar altimeter height of 30,110 ft. The accuracy of the map scaling was stated to be ± 20 ft. at about 10,000 ft., ± 30 ft. at about 20,000 ft. and was not given for higher levels.

These trials of Hurst's suggest that heights given by the radar altimeter may be in error by quite significant amounts: but that, nevertheless, we shall be quite safe in attributing the great majority of the differences shown in Fig. 1 to errors in the pressure altimeter. The most conclusive evidence on this point is the large difference between the readings of the two pressure altimeters.

References

(1) D. Brunt, 1934. Physical and Dynamical Meteorology.

(2) W. G. Durbin, 1955. Some further determinations of the speed correction coefficients of aircraft thermometers made by M.R.F. (To be published).

(3) Charnley and Fleming, 1949. Corrections applied to air-speed indicator and altimeter readings for position error and compressibility effects. (R.A.E. Report No. Aero 2299).

(4) Weaver, 1949. The calibration of air speed and altimeter systems. (Report No. A.A.E.E./Res/244).

(5) K. W. Smith, 1952. The measurement of position error at high speeds and altitude by means of a trailing static head. (R.A.E. Technical Note No. Aero 2163).

(6) G. W. Hurst, 1955. Radio altimeter trials - 2. (Unpublished).

TABLE 1

Difference Radar minus Pressure Altimeter Heights (ft.)

(a) Pilot's altimeter corrected for instrument, pressure and setting errors

Radar Altimeter Height (ft.)

Date	5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000
14/7/54	215	308	430	570	638	844	970	930	1,060	1,380
4/8/54	148	382	490	561	805	902	1,044	1,115	1,362	1,528
10/8/54	265	338	374	410	448	500	603	620	1,051	-
11/8/54	148	180	336	418	534	580	680	830	1,012	1,144
17/8/54	20	170	330	415	670	768	872	975	1,118	1,386
23/8/54	72	135	232	198	296	228	330	582	782	1,158
26/8/54	75	200	468	618	810	868	1,070	1,090	980	1,262

(b) Navigator's altimeter corrected as in (a)

Radar Altimeter Height (ft.)

Date	5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000
					2 mbs.					3 mbs
14/7/54	218	300	455	693	805	1,018	1,305	1,440	1,685	2,026
4/8/54	174	382	505	616	865	1,040	1,315	1,580	1,795	2,124
10/8/54	275	315	390	480	614	640	922	1,094	1,510	-
11/8/54	150	175	365	514	708	734	1,010	1,272	1,450	1,620
17/8/54	28	158	390	480	660	900	1,172	1,455	1,686	1,910
23/8/54	80	146	265	290	462	495	622	1,157	1,268	1,620
26/8/54	98	228	510	678	970	1,165	1,327	1,580	1,485	1,765

(c) Heights calculated from pilot's altimeter readings and temperature readings

Radar Altimeter Height (ft.)

Date	5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000	
14/7/54	165	145	165	210	120	172	192	110	200	320	190
4/8/54	35	65	35	-20	35	-7	62	22	150	143	13
10/8/54	240	292	292	252	243	308	378	202	443	-	
11/8/54	148	132	205	187	227	197	215	197	255	195	65
17/8/54	-40	-50	-45	-83	-2	2	-2	28	50	200	70
23/8/54	45	75	165	130	195	120	125	213	188	325	195
26/8/54	20	45	192	187	145	32	102	80	-50	130	00

Was change with ht of gravity allowed for? 130 ft. by 52,800 ft.

/(d)

G.23431(a)/JIJ/8/55/50.

(d) Heights calculated from the navigator's altimeter readings and temperature readings

Radar Altimeter Height (ft.)

Date	5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000	45,000	50,000
14/7/54	175	155	198	335	295	355	550	650	850	1,020
4/8/54	62	60	60	33	87	140	355	510	598	797
10/8/54	247	288	323	340	435	478	725	697	932	-
11/8/54	160	140	225	290	388	365	572	693	810	687
17/8/54	-33	-50	-10	-27	-2	110	303	520	648	752
23/8/54	62	90	200	210	340	252	468	793	720	820
26/8/54	57	87	230	245	310	332	383	590	500	685

TABLE 2

Extreme and mean values at 5,000 ft. and 50,000 ft. for the figures of Table 1

	5,000 ft.			50,000 ft.		
	Maximum	Minimum	Mean	Maximum	Minimum	Mean
From Table 1(a)	265	20	135	1,528	1,144	1,310
From Table 1(b)	275	28	146	2,124	1,620	1,844
From Table 1(c)	240	-40	87	325	130	235
From Table 1(d)	247	-33	104	1,020	687	794

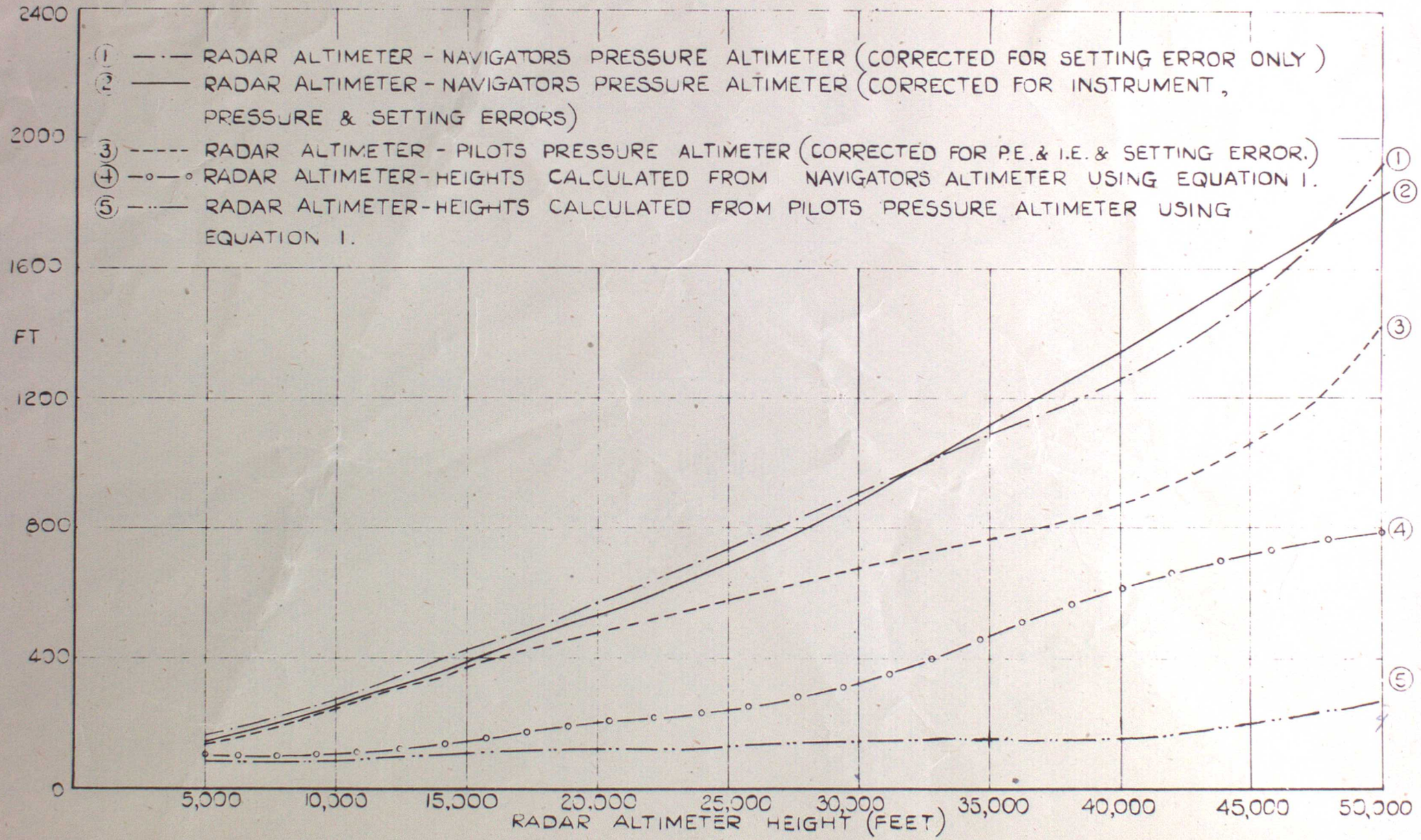

FIG. 1. DIFFERENCES BETWEEN RADAR ALTIMETER & PRESSURE ALTIMETER HEIGHTS (MEANS).

FIG. 1.